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United States
Department of
Agriculture

Forest Service

Intermountain
Research Station

General Technical
Report INT-213

September 1986

Sediment Rating Equations: An Evaluation for Streams in the Idaho Batholith

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RESEARCH SUMMARY

Sediment data collected on streams from National Forests and a watershed research study area in the Idaho batholith were used to develop suspended, bedload, and total sediment rating equations. This report discusses the statistics associated with 125 suspended, 121 bedload, and 119 total sediment rating equations. For streams where the timing and amount of management activities within the watershed were documented, any shifts in rating equations were compared with the timing of these activities. Some shifts in rating equations coincided with the occurrence of management activities while others did not.

Sediment yields were estimated using rating equations and a time-integration technique for data from the Boise National Forest. The two methods gave significantly different estimates of total annual sediment yield. For the research data the same predictions were made and compared with estimated sediment yield from sediment dams at the mouths of the drainages. The rating equation and time-integration techniques estimated similar sediment yields that were also similar to those from the sediment dams. However, the time-integration estimates more closely matched those from the sediment dams.

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INTRODUCTION

Sediment transport rates in streams and rivers have been measured for various reasons for many years. The U.S. Army Corps of Engineers began sediment sampling as early as 1838 in relation to navigation work on the Mississippi River (Livesey 1975). Most of the early sampling was done by groups such as the Corps, the Bureau of Reclamation, and the Soil Conservation Service (SCS) in response to the Flood Control Acts of 1928 and 1936. The purpose of the sampling was to predict sediment yields for planning flood prevention and control, water storage facilities, and large river basin studies. The sediment rating curve method of sediment prediction was developed in the 1930's. It was used extensively by the Corps of Engineers (Livesey 1975), the Bureau of Reclamation (Strand 1975), and the Soil Conservation Service (Holeman 1975) for large river analyses during the 1930's and 1940's.

In the 1940's and 1950's, emphasis in the Corps began to change from large river analyses to smaller watersheds. At the same time, analyses were being completed on an ever-increasing number of sites with shorter times from planning to implementation. This caused a shift from the rating equation method to the use of predictive equations correlating sediment yield from reservoir surveys to physical watershed characteristics and management activities. The SCS has moved away from the rating equation method due to shorter analysis times and to the variability of the sediment-discharge relationship (Holeman 1975).

Land management agencies have become increasingly involved in sediment measurements over the last 30 years. Sediment in streams was identified as a pollutant in the Federal Water Pollution Control Act Amendments of 1972 (PL 92-500). This and the passage of the National Forest Management Act of 1976 (NFMA) created a need to quantify sediment production, especially from National Forest lands. The development of Forest land management required quantified estimates of sediment yields. State water quality laws also became more specific in relation to sediment.

Suspended sediment measurement techniques have been well described and tested since the 1940's. Effective bedload measurement methods have only recently been developed. For this reason discussions regarding sediment rating equations in the literature have been restricted to suspended sediment rating equations. Also, much of the sediment data collected in the past are from large river systems where bedload sediment accounts for only 5 to 10 percent of the total sediment load (Anderson 1975; Emmett 1975). Rannie (1977) notes that even though the suspended sediment rating equation has received nearly universal acceptance as a hydrologic and geomorphologic tool, the curves themselves have received little attention. Rating curves are usually reported for individual studies with no general standards for comparing them with curves developed elsewhere. Rannie used watershed characteristics to predict rating equation coefficients. This follows from the assumption that suspended sediment is derived mainly from processes that operate throughout the watershed and that are imposed upon the channel, versus bedload transport, which is more dependent on channel hydraulics.

There has been limited application of sediment rating curves for small streams in the Northern Rocky Mountains. Much of the work is from third-order streams underlain by highly metamorphosed sedimentary rocks and glaciated granitics. Bedload makes up only 5 percent of the total sediment load from these watersheds (Rosgen 1980). Little attention has been given to the reliability of the sediment rating curves or to the statistics associated with the regressions.

This paper discusses sediment rating curves for streams in the Idaho batholith region. The granitic bedrock in this region is highly weathered, and the resulting soils are shallow, coarse textured, and noncohesive, which results in high erosion rates. The annual sediment yield contains 60 to 70 percent bedload. This paper will discuss the statistical reliability of the rating equations, their usefulness in monitoring watershed response to management, and their effectiveness in determining sediment yields, and will compare different techniques for estimating sediment yields.

Suspended sediment rating equations take the form:

$$Q_s = aQ^b \tag{1}$$

where:

Q_s = sediment concentration
Q = stream discharge
a and b = coefficients.

Flaxman (1975) described watersheds in relation to the value of *b*. However, when *b* became small, a nearly independent relationship between discharge and sediment concentration resulted. An unlimited supply of fine sediment in the streambed and banks might result in low-flow and high-flow sediment concentrations of equal magnitude. Flaxman developed a significant predictive equation for *a* using average annual runoff and the *b* coefficient. He then predicted undisturbed suspended sediment rating equations for three Western United States streams by assuming a value for *b* for undisturbed conditions. These curves were then compared with rating curves developed from sample data on these watersheds, which have undergone development. The difference between the predicted curves and the actual curves was attributed to development impacts.

Rosgen (1980) presents one method for predicting relative changes in potential sediment discharge from silvicultural activities using sediment rating curves. This procedure assumes that sediment rating curves are constants. But when used in conjunction with predicted streamflow increases following disturbance, the procedure can predict relative changes in sediment following silvicultural activities. The fact that shifts do occur in sediment rating curves due to disturbances and floods is recognized, but this procedure does not predict these changes.

The role of sediment supply in determining the sediment rating curve has gained increasing attention. Shen (1972) noted that for large rivers carrying mostly suspended sediment and little bedload, sediment transport of the river is more dependent upon supply from the watershed than on transport capacity. The amount of fine sediment in streamflow is more dependent on the intensity and location of rainfall, cover conditions, and other watershed factors than on water discharge. Bedload sediment derived from channel erosion should be more closely correlated with streamflow (Holeman 1975). Van Sickle and Beschta (1983) propose a supply-based model for small streams that uses the suspended sediment rating curve and a supply depletion function. The supply function expresses a declining suspended sediment concentration to reflect storm hysteresis and seasonal decline of sediment supply.

Simultaneous measurements of sediment and streamflow are required to develop a sediment rating equation. The intended use of the rating equation dictates how these measurements are taken. If an average annual sediment yield estimate is desired, the sediment and discharge should be taken over several years (if time permits) and include a wide range of flows. The resulting composite sediment rating curve can be used with a long-term flow duration curve to estimate the expected annual sediment for a typical year. Streamflow is not always available for the entire year or period of sediment measurement. If it isn't available, the flow duration curve must be developed by correlating the instantaneous streamflow measured in conjunction with sediment sampling with streamflow records of a nearby gauging station. Extreme hydrologic events (floods and droughts) and management impacts can significantly affect sediment discharge. Sediment rating equations developed from data collected during these events may not reflect average conditions. This should be remembered when analyzing data for sediment rating equation development.

If the intended use of the rating curve is to estimate yearly sediment yields, or to monitor the effects of watershed disturbances on sediment yield, or both, annual rating curves should be developed. Actual or estimated streamflow for each year is used to estimate annual sediment yield. Estimates of streamflow could again be obtained by correlation with nearby gauging station records. In this case, mean daily flows are used in the sediment rating curve to calculate daily sediment. The daily sediment values are added to estimate annual sediment yield.

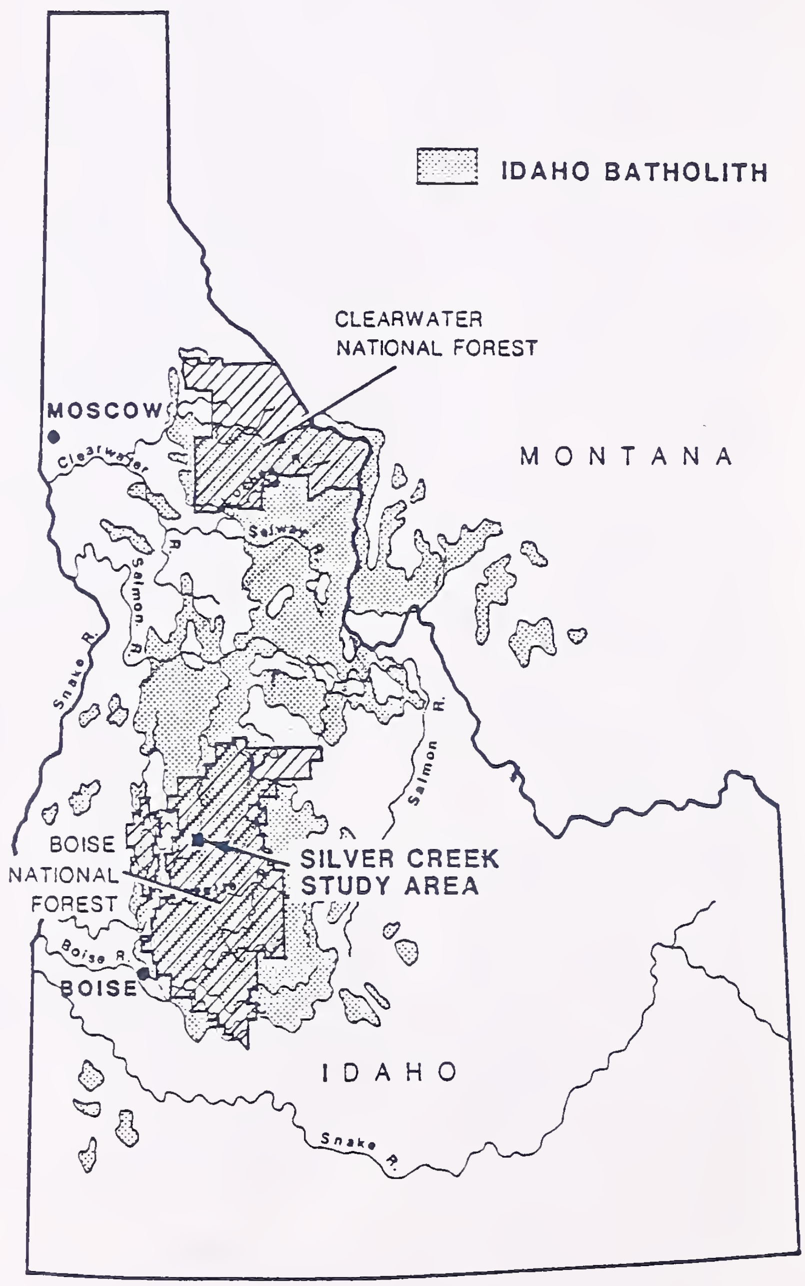

Figure 1—Locations of the Idaho batholith, Clearwater and Boise National Forests, and Silver Creek study area in Idaho.

THE DATA

The sediment rating curves discussed in this paper are derived from data collected on the Boise and Clearwater National Forests and from watershed research in the Silver Creek area (fig. 1). The Idaho batholith is within the Northern Rocky Mountain Geomorphic Province. The streams on the Clearwater National Forest are within the Lochsa Uplands section and are characterized by moderate slopes (30 to 50 percent) with steeper lower canyon areas draining the rejuvenated uplands. The streams on the Boise National Forest, which includes those in the Silver Creek area, are in the southern batholith section where steep, strongly dissected slopes (50 to 70 percent) dominate. Streamflow and sediment transport reach a peak in response to melting winter snowpacks during April and May. Intense summer thunderstorms occasionally cause significant flow increases, but these and the associated sediment discharge are small relative to the spring snowmelt peaks. For information on precipitation and streamflow for these areas, see Idaho Water Resources Board (1968).

The data include instantaneous suspended and bedload sediment and concurrent streamflow. Suspended sediment is sampled with DH-48 depth-integrating samplers. Helley-Smith samplers are used for sampling bedload sediment. Streamflow is measured each time with current meters.

Forest Data

Sampling on the Boise and Clearwater National Forests was concentrated around the spring snowmelt peak with samples taken infrequently during the summer and fall months. The number of samples per year varied from five to 20 with a mean of 10. Sediment rating curves were developed for suspended, bedload, and total sediment for each year of record and for the period of record. Total sediment rating curves were developed by regressing discharge on the sum of the DH-48 and Helley-Smith sediment values. The 10 streams on the Boise National Forest had 3 to 5 years of record. Seven streams included in this report from the Clearwater National Forest had 3 to 8 years of record. All streams had various levels and ages of land management. The watersheds varied in size from 244 to 2,298 ha.

Two methods were used to calculate sediment yield. The rating equation approach required continuous streamflow records for the monitored stream, or a correlation between instantaneous flows measured on the monitored stream with mean daily flows from a nearby stream gauge. If the correlation was good ($R^2 \geq 0.60$), the gauged stream was used to generate streamflow values for the sediment rating equation. The rating equation method integrates based on streamflow fluctuations. Stream gauge records did not correlate well with the streamflow measurements on the Clearwater National Forest, so sediment yields are not presented for these streams.

The second method, in this paper called the time-integration method, ignores streamflow fluctuations and integrates over time. Sediment discharge measured at two consecutive sample dates was averaged and multiplied by the time elapsed between the two hand samples. When a sample taken during high sediment discharge covered a long period (>10 days), the time was adjusted based on what the analyst knew about the position of the sample on the hydrograph and the shape of the hydrograph. This adjustment reflected the tendency for peak flows and high sediment discharges to be short lived.

Research Data

Data were collected in the Silver Creek study area in central Idaho. Streamflow and sediment were measured as described above except that measurements in Silver Creek were taken in a rectangular flume to provide a more uniform cross-section and flow distribution. Sampling was limited to the spring snowmelt period with an average of 15 samples of suspended and bedload sediment each year. The period of record for Silver Creek spring sediment monitoring ranged from 3 to 5 years. These third-order streams drain watersheds of 109 to 186 ha.

Sediment rating equations were developed for suspended, bedload, and total sediment by regression as described for the Forest monitoring data. Sediment yield for Silver Creek streams was computed as above, but in this case mean daily flows were available for each stream.

In addition to the hand sediment samples taken during spring snowmelt, automatic pumping samplers were in operation during most of the year in Silver Creek. Discrete samples were pumped from a hydraulic jump in the flume on a timed basis. The sampler intakes were located 1 to 2 cm from the bottom of the flume to provide an estimate of total sediment load rather than just suspended sediment load. The interval for sampling varied from 1 to 24 hours. The interval was changed manually in response to streamflow changes or precipitation or both. From 26 to 460 samples were taken per stream each year during 4 years. Sediment rating equations were developed from these data as well. The large number of samples made it feasible to group the data by rising and falling limbs of the hydrograph, by storm, and by time, in an attempt to reduce the variance in the data. Sediment yields were estimated using detailed storm-by-storm rating equations, from more general seasonal equations, and by time integrating.

To validate sediment yield estimates from hand samples and pumping samplers, all values were compared with sediment yields from sediment dams located just downstream from the flume in each watershed. The volume of sediment in each sediment dam was converted to mass using volume-weight estimates from core samples of the trapped sediment. This was then corrected for the trap efficiency of the reservoirs. The results are believed to be the

best estimate of actual sediment yield from the watersheds.

RESULTS AND DISCUSSION

Analysis of the data from the Boise and Clearwater National Forests resulted in 87 suspended, 83 bedload, and 81 total sediment rating equations ($Q_s = aQ^b$). Thirty-eight equations of each sediment type were derived from the Silver Creek data.

Rating Equation Success

The number of equations that were statistically significant at the 95 percent level of confidence varied by sediment type (table 1). An arbitrary criterion was used to establish "useful" equations. Equations were used to predict sediment yield if the explanatory (independent) variable, Q, explained at least 60 percent of the variation in the response (dependent) variable, Q_s (that is, $R^2 \geq 0.60$). The better controlled sampling conditions in Silver Creek should have provided data that define the sediment-discharge relation more accurately. However, the variability of sediment discharge was no better defined by the regressions on streamflow in Silver Creek than at the natural cross-sections on the two Forests (table 1).

Significant relationships were much more evident for bedload sediment than for suspended sediment. This supported the observations of Shen (1972), Holeman (1975), and Rannie (1977) that suspended sediment discharge on large rivers was more dependent on watershed properties and perturbations than on streamflow, and that bedload should be more closely correlated with streamflow. Only 11 percent of the suspended sediment equations but half of the bedload equations had $R^2 > 0.60$. Total sediment load rating equations fared much better on the National Forests than in Silver Creek; 78 percent versus 47 percent had $R^2 > 0.60$. The research watersheds were typically smaller than the monitored watersheds on the Forests, but no correlation was found between watershed size and rating equation success.

All suspended sediment regressions in this paper used sediment concentration in milligrams per liter (mg/L) and streamflow in cubic feet per second (ft^3/s). Sometimes suspended sediment is reported as a rate, such as kilograms per hour (kg/h). If this rate is regressed against streamflow, the coefficient of determination will be considerably higher than if the same data in milligrams per liter were used. The result, however, is a spurious self-correlation because the conversion of concentration, milligrams per liter, to a rate in kilograms per hour involves streamflow (Kenney 1982). The regression using kilograms per hour is really aQ vs Q. The self-correlation of Q vs Q does not alter the sediment concentration predicted using streamflow. But a cause-and-effect relationship between the two, with properties of the resulting equation, cannot be claimed.

The rating equations for total sediment were also plagued by spurious self-correlation because suspended sediment concentration must be converted to a rate before being added to the bedload component. This problem is unavoidable with current sampling devices that measure suspended sediment as a concentration and bedload as a rate.

Several factors may contribute to the low success rate for the rating equations. First, the sample size was small, typically 15 or less. With small samples, the table t value becomes large due to the small degrees of freedom. This makes it more difficult to show statistical significance. A related problem may be that the 10 to 15 samples did not adequately sample the hydrograph to define a good sediment-discharge relationship. The hysteresis effect may be inherent in the data, even though there are not enough data points to analyze for these effects. The presence of hysteresis merely adds to the variance due to concentration.

Various levels of management activities existed prior to and during the period of monitoring on most of the Forest watersheds. This could continually vary the sediment supply to the streams such that a good sediment-discharge relationship for a given year may not exist. In the research area, however, management activities were controlled. Most of the drainages were undisturbed for 2 or 3 years and then impacted with specified levels of management. The introduction of disturbances in these small watersheds did not have an adverse effect on the rating equation success. The rating equation success increased slightly after management activities occurred in the drainages. Because these drainages

Table 1—Statistical significance of sediment rating equations in the Idaho batholith

Location	Sediment type[1]	No. rating equations	No. significant rating equations[2]	(%)	No. significant rating equations w/$R^2 > 0.60$	(%)
National Forests[3]	SS	87	38	(44)	10	(11)
	BL	83	59	(71)	47	(57)
	Tot	81	71	(88)	63	(78)
Silver Creek	SS	38	18	(47)	4	(11)
	BL	38	27	(71)	16	(42)
	Tot	38	30	(79)	18	(47)

[1]Type of sediment: SS = suspended; BL = bedload; Tot = total sediment.
[2]Significant rating equations are those with coefficients that are significant at the 95 percent level of confidence.
[3]Data from granitic watersheds on the Clearwater and Boise National Forests, Idaho.

were supply-limited prior to management, the introduction of accelerated sediment could produce a more continuous supply of sediment and actually improve the sediment-discharge relationship.

Channel sediment storage may impact the quality of the sediment-discharge relationships because storage was not accounted for in the equations. Van Sickle and Beschta (1983) discussed the importance of channel bed forms and large organic debris as storage sites for both suspended and bedload sediment. Noting this, they proposed a supply-based model for small streams that uses the suspended sediment rating curve and a supply depletion function. The supply function expresses a declining suspended sediment concentration to reflect storm hysteresis and seasonal decline of sediment supply. Megahan (1982) found an average of 15 times more sediment stored behind obstructions in channels than was delivered to the mouths of the drainages. This suggests that sediment movement is dependent on the dynamics of channel storage components and not just streamflow. It is likely that fluctuations in these storage components during high flows limit the effectiveness of the bedload sediment rating curves.

A more appropriate bedload sediment rating equation should include a constant to define at what streamflow bedload sediment movement is initiated. This plus the introduction of a sediment storage factor might significantly increase the success rate of bedload sediment rating equations.

As mentioned, automatic pumping samplers were used in Silver Creek in addition to the hand samples. Sediment rating equations were developed for these data as well. Six streams with 4 years of record resulted in 23 rating equations. A total of 74 percent or 17 of the equations were significant; only five equations had an R^2 greater than 0.60. The large number of automatic samples made it possible to divide the samples into groups. This was done for rising and falling limbs of the hydrograph around the annual snowmelt peak, for all peaks, and on a seasonal basis. The seasons used were fall (September to mid-November), winter (mid-November to mid-March), spring (mid-March through May), and summer (June through August). These divisions will not be discussed in detail. However, the success rate for these rating equations was: of 278 equations, 62 percent were significant; 24 percent had an R^2 greater than 0.60.

Figure 2 is an illustration of the equations from grouping the data by rising and falling limbs for each peak over a year. The lines labeled 4R and 4F are the rising and falling limb rating curves, respectively, for the snowmelt peak. Curve 1F is a falling limb at the beginning of the water year and is not statistically significant at the 95 percent level of confidence. Curves 2R and 2F represent an early winter rain, 3R and 3F represent a February thaw, and 5R and 5F result from spring rains.

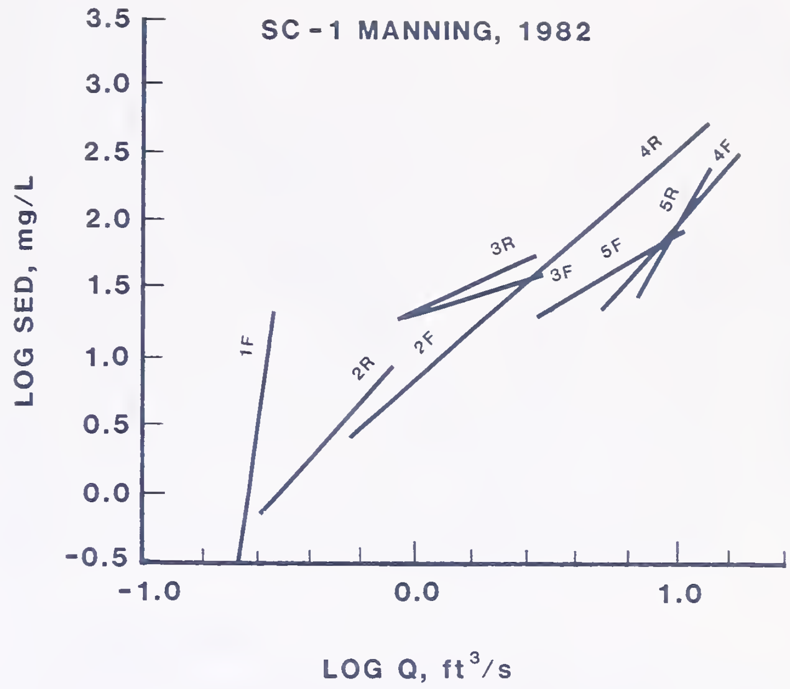

Figure 2—Suspended sediment rating curves based on individual rising and falling limbs of an annual hydrograph. R = rising; F = falling; numerals indicate chronological order of the hydrograph peaks. The extent of the curves indicates the limits of the data.

Documenting Management Effects

Previous analyses have indicated that floods and management activities cause shifts in suspended sediment rating equations (Flaxman 1975; Rosgen 1980). In the handbook, "An Approach to Water Resources Evaluation of Non-point Silvicultural Sources," Rosgen (1980) presented one such analysis for the Needle Branch watershed in Oregon. Rating curves shifted following the 1964 flood and subsequent clearcutting operations. No statistical information was presented regarding the significance of the observed changes in the rating equations. In the following examples from the Idaho batholith, the influence of management on both suspended and bedload sediment rating equations will be discussed in terms of statistical significance.

In Silver Creek, 38 ha were harvested on south aspects in watershed SC-6 (163 ha). The units were clearcut and yarded by helicopter in the fall of 1976. The following year was extremely dry and no instream sediment was sampled, so 1978 is the first posttreatment year for which sediment rating equations were developed. The suspended sediment rating equations (fig. 3a) indicate that a shift to a steeper slope may have occurred between 1976 and 1978. However, the two curves are not statistically different at the 95 percent level of confidence. No statistical change in sediment yield occurred at the sediment dam following the timber harvest.

The only curve in figure 3a that is statistically different from any of the others is the 1982 curve. It differs from both the 1975 and 1980 curves in slope

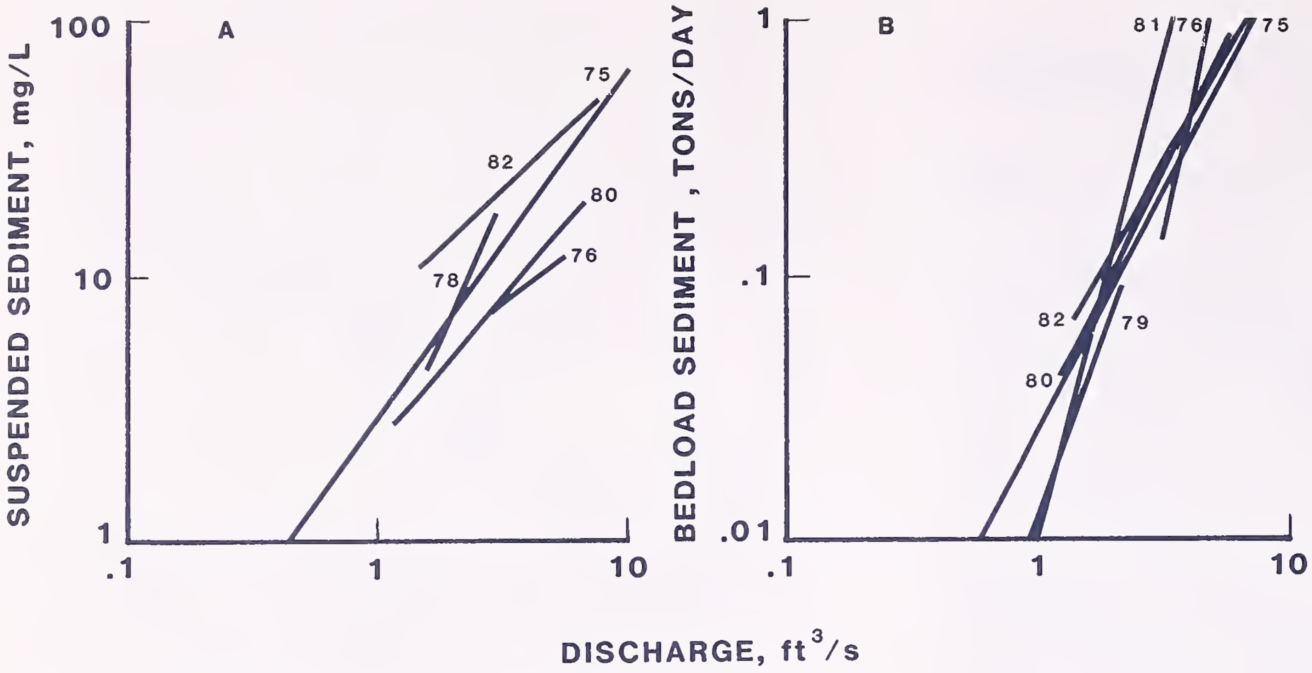

Figure 3—Sediment rating curves for stream SC-6 in the Silver Creek study area. The extent of the line indicates the limits of the data.

only. Interestingly, it is not significantly dif.erent from the 1978 curve due to high variability The shift in the 1982 suspended sediment curve does coincide with a statistically significant increase in sediment yield at the sediment dam. This delayed sediment yield increase at the mouth of watershed SC-6 is likely due to sediment storage along the channel with a subsequent release of the stored material by greater than normal spring runoff in 1982. In this case, the change was documented through a shift in the rating equation. However, it is not likely that the stream would be sampled for 6 years under normal monitoring programs on the typical forest.

The bedload curves for the stream in watershed SC-6 (fig. 3b) show two distinct groupings: the 1976, 1979, and 1981 curves appear to be a separate group from the other three in terms of slope. The only statistical differences are that the slope for 1979 is different from 1975 and 1982. The 1978 data do not produce a significant equation. Although the 1981 curve is statistically significant, the variance about the equation is large, resulting in wide error bands. This explains why it does not test significantly different from the other equations. Any effect the timber harvest had on the bedload rating equations is not discernible.

During the summer of 1980, a kilometer of road construction within proximity of the stream channel in watershed SC-4 (102 ha) was completed. The rating equations appear to shift in response to this (figs. 4a and 4b). The 1981 rating equations for both suspended (fig. 4a) and bedload (fig. 4b) sediment are significantly different from the rest of the years. The 1981 suspended sediment curve differs only in slope, while the bedload curve differs both in slope and intercept. The 1982 curves suggest a recovery to near preroad construction conditions, despite continued sediment delivery to the channel from the road that year.

Bedload sediment rating equations for the stream in watershed SC-2 (118 ha) show a significant slope reduction between 1979 and 1980 with apparent recovery in 1981 and 1982 (fig. 5). There was no management activity in this drainage during this time. Suspended sediment rating curves are not shown because only one equation from 5 years of record was significant.

Documenting management effects on sediment rating equations from the two Forests was more difficult because records of exactly when the activity occurred were not readily available. The date when the contract was awarded was available, but the actual operation may have taken place a year or more later. For this reason, an analysis of Forest data with respect to management effects on rating equations is not presented here.

The problems encountered above may be due more to the data than to rating equations in general. However, the data used in the above analyses are typical of sediment data collected on National Forests in the Intermountain West. Shifts in sediment rating curves based on small sample sizes may result from differing ranges of streamflow over which data are collected from year to year. This is somewhat unavoidable depending on the range of flows present each year. However, sampling should encompass the same range of flows as much as possible each year. Otherwise, being on a different portion of the logarithmic curve could provide a different equation. The change in curves may also result when sample variance is high and small sample sizes do not adequately sample the variance. A third reason for change in curves is a real change in the sediment-discharge relationship.

Using sediment rating equations as the sole evidence for management impacts is not advised. The effects of sample size and sampling scheme on the equations may not be completely separable from the effects of management on the sediment-discharge relationship. Few if any forests will be able to collect enough samples to alleviate

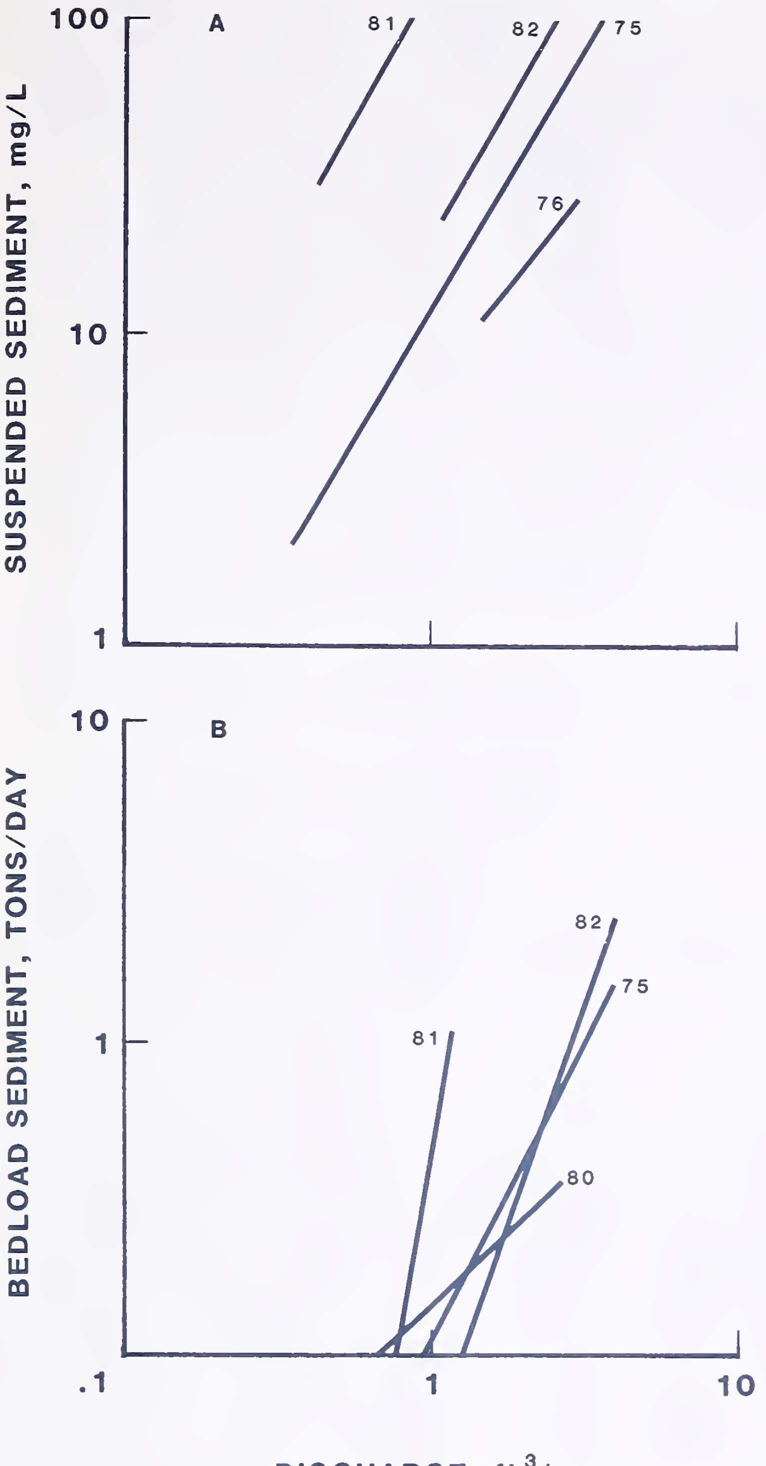

Figure 4—Sediment rating curves for stream SC-4 in the Silver Creek study area. The ends of the curves indicate the limits of the data.

the statistical problems surrounding small, variable sample sets. However, if used with other forms of evidence, a rating equation may provide valuable, additional documentation.

Sediment Yield Estimation

One of the basic purposes for developing a sediment rating equation for a stream is to estimate sediment yield. The sediment rating equation is used to predict an appropriate sediment rate for periods when no sediment data are available but streamflow is available or can be accurately estimated. For sediment yield estimates in this paper, mean daily streamflow values were used with

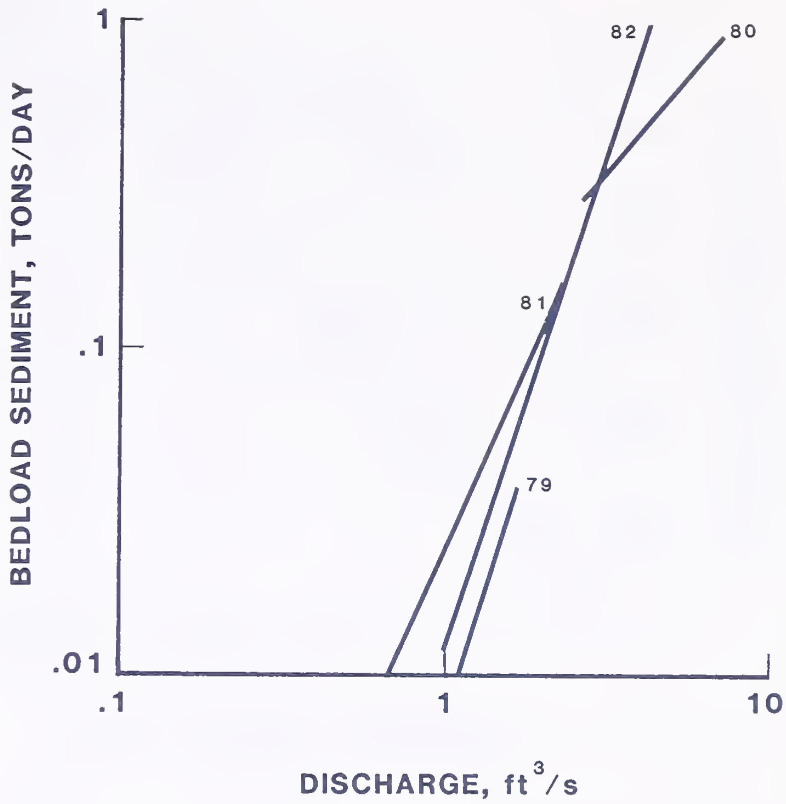

Figure 5—Bedload sediment rating curves for stream SC-2 in the Silver Creek study area.

the sediment rating equations. Streamflow for the monitored streams on the Boise National Forest was derived from U.S. Geological Survey gauging stations in the vicinity. Continuous streamflow records were available for the streams in Silver Creek.

The two methods used to estimate sediment yield for streams on the Boise National Forest yielded somewhat different results (fig. 6). The time-integration technique typically yielded higher values than the rating equation approach. A paired *t* test showed that the difference between the two methods was significant at the 95 percent level of confidence. Because there was no known true value for sediment yield from these watersheds, no evaluation of which estimate was more accurate could be made.

The time-integration method probably averages higher because samples taken at or near peak sediment movement are generally averaged over longer periods than may be appropriate for that level of sediment transport. Timing of the samples is important because a single sample must be representative of the prevailing conditions, in some cases for many days. The rating equation is also affected by the timing. However, the effect may not be in the same direction or be as significant for the rating equation because all sample points are analyzed as a group. Each sample carries more weight in the time-integration method. Walling (1977) discovered gross overestimates of total load using sediment rating curves for three British rivers. However, monthly suspended loads were both overestimated and underestimated based on rating equations, with overestimates predominating.

Sediment dams at the mouths of streams in the Silver Creek study area provided a base sediment yield estimate to compare with estimates from different methods.

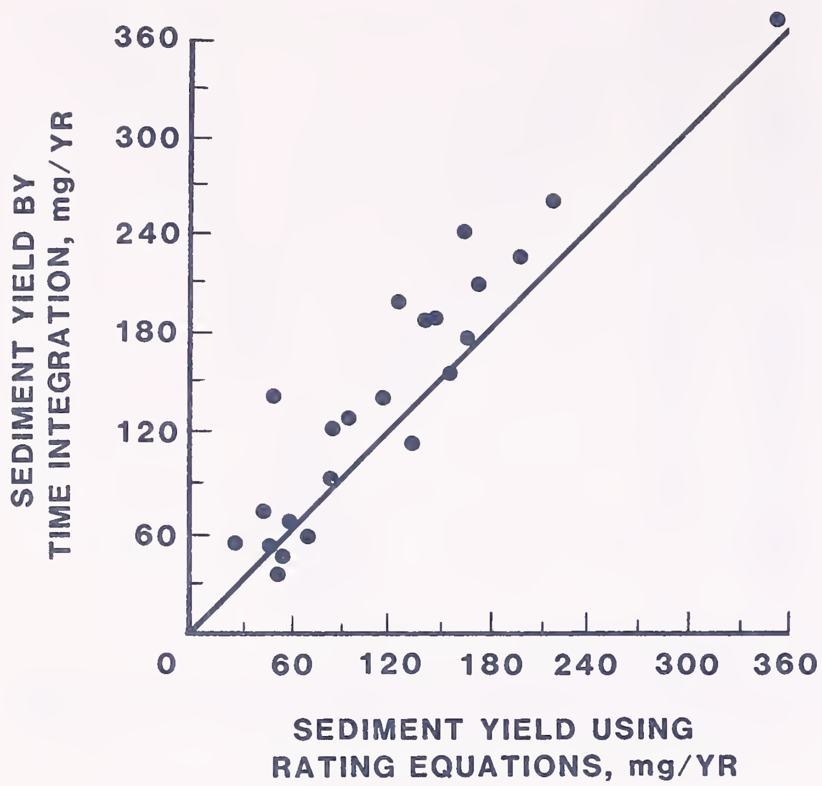

Figure 6—Comparison of sediment yield estimates from two methods: (1) by using sediment rating equations and (2) by time-integration between hand samples. Data from stream monitoring on the Boise National Forest.

Five estimates of sediment yield were made from the data in Silver Creek (table 2). The first method used a sediment rating curve for total sediment from the hand samples and mean daily streamflow. The second method time-integrated total sediment as described above for the Boise National Forest data. The third and fourth methods were the same as the first two with the exception that the automatic pumping sampler sediment data were used. The fifth method estimated sediment yield based on the volume of sediment in sediment dams.

The equivalency of the rating equation method and integration method for the hand samples was tested with a paired *t* test. The hypothesis that the two methods give the same estimates was accepted at the 95 percent level. However, as with the Forest monitoring data, the time-integration method averaged slightly higher yields than the rating equation method (fig. 7). The sediment yields from these two methods are compared with the sediment dam yields (fig. 8), and neither tested different from the sediment dam yields at the 95 percent level. But the yield estimates from the rating equations did test different at the 90 percent level. Although the differences were not significant by the paired *t* test, the sediment dam yields were somewhat less for years of low sediment yields and greater for high sediment years than the estimates by rating curves and integration. The paired *t* test only tests the means, so the variances could be different.

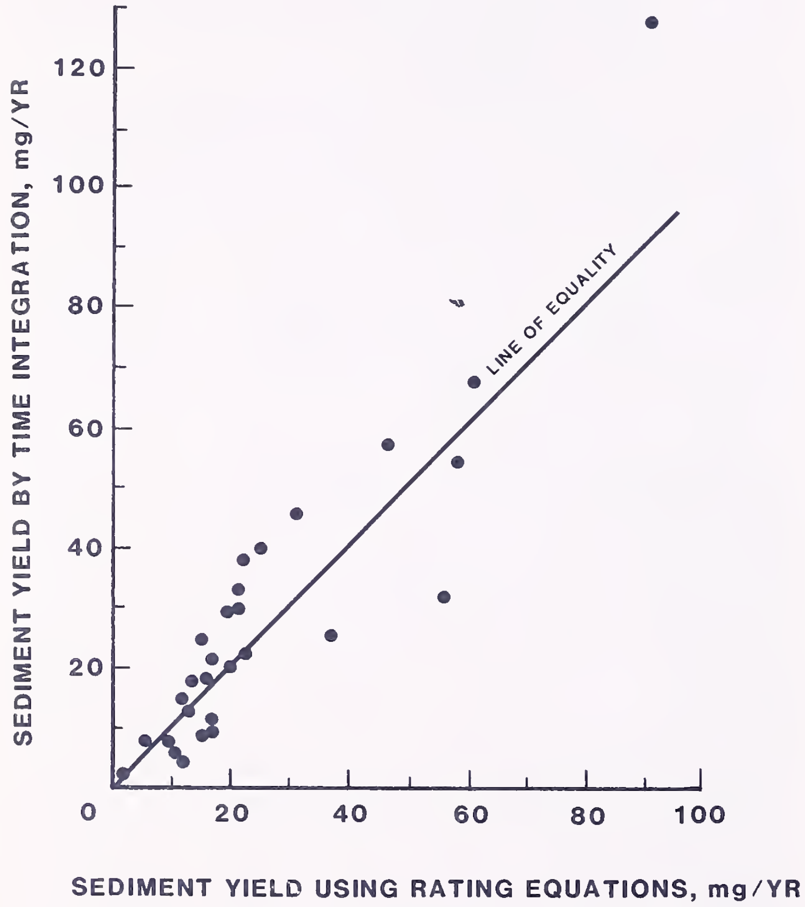

Figure 7—Comparison of total sediment yield estimates from two methods: (1) by using sediment rating equations and (2) by time-integration between hand samples. Data from streams in the Silver Creek study area.

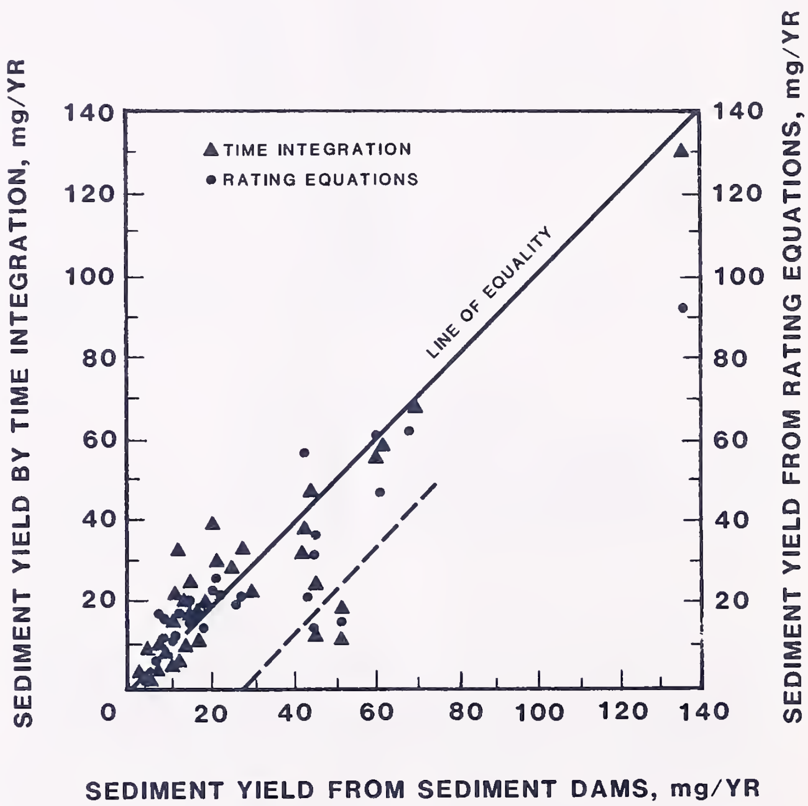

Figure 8—Comparison of sediment yield estimates using time-integration, rating equations, and sediment dams from Silver Creek data.

Table 2—Comparative sediment yields for Silver Creek streams, Idaho

Stream	Year	Total sediment yield estimates in megagrams per year: Hand samples, Rating equations	Hand samples, Time integration	Sediment dam yield	Pumped samples, Rating equations	Pumped samples, Time integration
SC-1	78	13.8	17.1	16.8		
	79	5.4	7.3	5.3	1.9	2.1
	80	31.2	45.3	44.6		
	81	16.2	10.7	15.4	5.3	3.4
	82	46.9	57.2	61.1		
SC-2	78	16.7	9.3	7.2		
	79	1.5	1.5	3.4	.7	.6
	80	22.0	38.0	42.8	5.6	1.2
	81	10.3	5.3	9.3	2.1	2.5
	82	59.0	54.3	60.1		
SC-3	75	20.1	19.8	14.4		
	76	16.7	20.9	11.4		
	78	—	8.9	11.9		
	79	—	1.6	2.9	2.2	.6
	80	14.9	24.8	14.1	1.5	4.1
	81	11.1	4.4	7.3	1.6	2.6
	82	56.2	31.8	41.8		
SC-4	75	22.7	21.3	19.3		
	76	—	22.0	27.8		
	78	—	11.2	50.4		
	79	—	2.6	4.5	1.0	.7
	80	15.6	18.0	50.6	8.7	14.4
	81	12.5	12.0	43.5	7.0	16.6
	82	91.1	128.6	135.9		
SC-5	75	—	32.3	12.1		
	76	—	18.9	17.4		
	78	—	15.0	13.6		
	79	—	1.3	2.7	1.6	1.9
	80	11.8	14.3	10.6	11.9	13.7
	81	15.2	8.8	8.5	2.9	4.8
	82	36.8	24.9	44.4		
SC-6	75	19.4	28.7	25.6		
	76	21.1	32.6	26.9		
	78	21.0	29.5	21.0		
	79	1.5	1.9	3.5	1.5	1.2
	80	25.3	39.8	20.8	10.3	12.0
	81	9.5	7.4	9.1	4.3	3.1
	82	61.2	67.9	68.9		

The large variance associated with sediment data may have masked differences in estimates from various techniques, but the differences did exist. Only 26 percent of the time-integration estimates and 21 percent using rating equations were within 10 percent of the sediment dam estimates. Table 3 shows that nearly 50 percent of the estimates were within the 25 percent error band, but also that some estimates were 100 percent or more different.

Several factors were used to try to explain why some sediment yield estimates from rating equations were within 10 percent of "actual" while others were more than 50 percent different. These included the number of samples on the rising versus the falling limbs of the hydrograph, statistical significance of the suspended sediment and bedload equations, and the sample year.

Table 3—Percentages of sediment yield estimates within specified error bands around the sediment dam estimates

Percent error	Percent of estimates within given error: From rating equations	From time integration
10	21	26
25	55	45
50	76	74
80	97	92
100	97	97
150	100	97
200		100

No trends were established, and it appeared that it was a matter of chance that the sediment yield estimates were close to the sediment dam yields. The most severe underestimation of sediment yield by both methods was for the first 2 years after road construction in watershed SC-4 and for years of high annual water yield in some watersheds. These are the data points below the dashed line in figure 8. This was probably the result of too few samples to accurately define the sediment-discharge relationship following disturbance and at times of active channel bed movement. During higher than normal streamflow, channel sediment storage features may break up and re-form. This may release pulses of sediment that were not measured by weekly or every-other-day sampling. This again points out the importance of storage in these high-energy third-order streams.

Because the time-integration method appears to estimate sediment yield as well as the rating equations but does not require continuous or mean daily flow records, this method is probably more desirable for use on ungauged streams and on gauged streams where good sediment rating equations cannot be developed. This conclusion is based on the results from the Silver Creek research watersheds just discussed. The same conclusion cannot be reached for the data from the Forests because there is no known value to check against. To make the time-integration method work, samples must be well distributed over the entire hydrograph so that highs as well as lows are sampled. Streams in Silver Creek were generally sampled every other day during snowmelt with a morning sample one time and an afternoon sample the next time. In this way not only the general hydrograph was sampled, but daily hydrograph variations were accounted for such that, by averaging the sediment rates of two consecutive samples, near average conditions were simulated. If all samples were taken near hydrograph peaks, sediment yield would be overestimated. On the other hand, if peak flows were not sampled, sediment yield would be underestimated. Poor sampling will provide erroneous estimates of sediment yield.

The number of samples necessary to characterize a hydrograph depends on flow conditions. In snow-dominated systems typical of the Northern Rocky Mountains, the majority of sediment transport occurs during spring snowmelt. This may be completed in 3 or 4 weeks one year and 6 or 8 weeks the next year. Generally, sampling during this melt period is sufficient to predict annual sediment, particularly in bedload-dominated systems, because this is the major time that streamflow is sufficient to transport bedload. Where suspended sediment is more important, samples may be required throughout the year because suspended sediment may frequently be mobilized during summer storms. Management impacts may produce readily available sediment that may be transported during the summer as well. This should be considered in sample collection planning.

The sediment yield estimates, based on the pumped samples and DH-48 hand samples, gave differing estimates, and these estimates are quite different from the sediment dam estimates (table 2). Pumping samplers are designed for sampling suspended load, but the intakes for these samplers in Silver Creek were in a hydraulic jump 1 to 2 cm from the bottom, in an attempt to sample bedload as well. Because of the large percentage of suspended sediment rating equations that were not significant, a comparison of suspended sediment yield from DH-48 samples and pumped samples was done using the time-integration method estimates (table 4). The correspondence of the paired sediment yield estimates was variable, but a paired t test indicated that the pumping sampler estimates were significantly higher than the hand samples at the 90 percent level. This suggested that because of the intake position, the pumping samplers were indeed sampling more than just the suspended sediment load of the streams. However, the pumping samplers were not fully sampling total sediment when compared with the sediment dams (table 2).

The detailed analysis of rising and falling limbs of the hydrograph for the pumped samples did not provide enough significant rating equations to model each storm event during the year. Also, many of the significant equations that resulted from five to 10 samples on a rising or falling limb covered such a narrow range of discharge that extreme caution was necessary when predicting sediment. So narrow were many of these discharge ranges that the equation was not useful for prediction. This was probably because the relationship between the five to 10 sediment concentrations and discharges had a high variance, and therefore the true line may have been much different. Many of these relationships had extremely low coefficients of determination. Less than half the significant equations had coefficients of determination of 0.60 or more. The best results were achieved by dividing the data set at the annual snowmelt hydrograph peak or by season. In some years the most useful relationship resulted from using the entire data set.

Table 4—Comparison of suspended sediment yield estimates using DH-48 hand samples and automatic pumping sampler samples

Stream	Year	Sediment dam yield	Sediment yield by time integration: DH-48	Sediment yield by time integration: Pumping sampler
		Megagrams per year		
SC-1	79	5.3	1.9	2.1
	81	15.4	4.9	3.4
SC-2	79	3.4	.5	.6
	80	42.8	6.1	1.2
	81	9.3	2.1	2.5
SC-3	79	2.9	.6	.6
	80	14.1	2.7	4.1
	81	7.3	2.6	2.6
SC-4	79	4.5	.9	.7
	80	50.6	7.2	14.4
	81	43.5	6.1	16.6
SC-5	79	2.7	.4	1.9
	80	10.7	2.1	13.7
	81	8.5	1.8	4.8
SC-6	79	3.5	1.1	1.2
	80	20.8	12.7	12.0
	81	9.1	2.4	3.1

As discussed earlier, annual sediment yields from total sediment rating equations were found to average less than the sediment dam yields at the 90 percent confidence level but not at the 95 percent level. Total sediment yield was also estimated by determining annual suspended sediment and annual bedload from the respective suspended sediment and bedload rating equations and adding the results. These estimates were somewhat less than those from the total sediment rating equations (fig. 9) and tested significantly less than the sediment dam estimates at the 95 percent confidence level. This data set, however, was smaller (n=17) than the earlier data set (n=29) because there were fewer years when both the suspended sediment and bedload equations were significant.

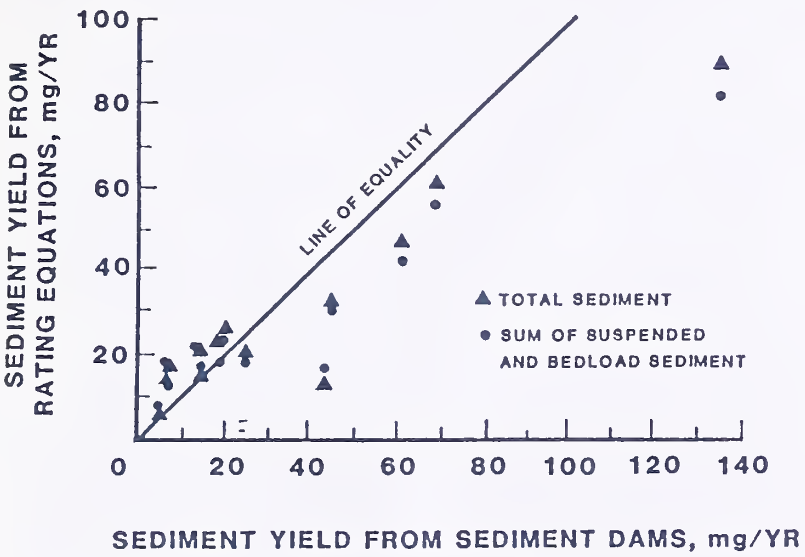

Figure 9—Comparison of sediment yield from sediment dams with sediment yield from total sediment rating equations and the sum of yields from suspended and bedload sediment rating equations. Data from Silver Creek watersheds.

CONCLUSIONS

Sediment rating equations similar to equation 1 that are based on small sample sizes are not in themselves reliable for documenting watershed disturbances in streams dominated by bedload sediment in the Idaho batholith. A large proportion (33 percent) of the rating equations developed during this evaluation were not statistically significant, and an additional 24 percent, while significant, were not "useful" because streamflow explained less than 60 percent of the variance in sediment. Year-to-year watershed response evaluations were extremely difficult. The large natural variance of sediment data resulted in rating equations with wide confidence bands. This made it hard to show statistical significance of suspected shifts in rating equations. Rating equations for a given stream changed from year to year. Sometimes the change could be attributed to activities in the watershed, but other times there was no apparent reason for the shift. It may have resulted from the sampling scheme or purely from sample variance.

In snowmelt-dominated and bedload-dominated systems, time integration of sediment yield from sample date to sample date can provide accurate estimates of annual sediment yields with as few as 15 or 20 well-taken samples. This requires that samples adequately describe the average conditions for which they apply. Misleading estimates of sediment yield will be obtained if sampling does not properly reflect streamflow and sediment transport distributions. Sampling schedules should be well thought out and flexible so that atypical runoff events can also be sampled. Thus, accurate sediment yield estimates can be expected using time integration. For the Silver Creek data, 74 percent of the estimates of sediment yield by time integration were within 50 percent of the sediment dam yields.

The use of pumping samplers to generate more samples does not necessarily increase the chances of having better predictive rating equations. Of the rating equations developed for pumped samples in Silver Creek, 62 percent were significant, and many of the significant equations had limited usefulness for predictions due to the small range in streamflow for which they applied. Pumping samplers with intakes positioned as those in Silver Creek do not adequately provide total sediment load samples. When placed close to the bottom of the stream they will sample some bedload but only enough to overestimate suspended sediment load.

Separate suspended and bedload sediment rating curves estimate smaller sediment yields than do the total sediment rating equations from the same data. Total suspended sediment equations appear to estimate too much sediment for low annual yield years, and increasingly too little sediment for greater sediment years.

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Sediment data from streams in the Idaho batholith were used to develop suspended, bedload, and total sediment rating equations. These equations are discussed in terms of statistical significance and their usefulness for documenting management impacts. Sediment yields were estimated using the rating equations and streamflow data. These yields were compared with those estimated from a time-integration method. For streams in the Silver Creek research area, sediment yields from rating equations and time-integration techniques were compared with estimates from sediment dams. Rating equation and time-integration estimates were statistically different. Time-integration estimates more closely matched those from the sediment dams.

KEYWORDS: rating equations, sediment, sediment yield, suspended sediment, bedload

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